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New Characteristics in the Assessment of Reliability of Machines and Devices

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Abstract
The aim of this work is to present new reliability characteristics expressed as functions of some variable expressing the measure of effective operation of a machine or a device. These characteristics can be used for both renewable and non-renewable objects. Their mathematical idea reflects the essence of already known characteristics, i.e. it expresses the probability of failure but expressed as a function of a variable, not necessarily identified with time.

Keywords
Reliability, Damage intensity function, Cumulative damage intensity function.

Introduction

In the maintenance strategy, especially of large companies in the engineering and transport industry, effective forecasting of vehicle or machine failure is an important technical problem (Młynarski, 2014; Młynarski & Oprzędkiewicz, 2012). In production, especially automated production, failure of one machine can cause significant complications in production organization. In transport, vehicles often transport "sensitive" goods over long distances due to transport time, e.g., fruit and vegetables or live animals; any unplanned stop is associated with a potential loss, it also affects the image of the company.

Knowledge of the causes of vehicle failures, the frequency of their occurrence, as well as the correlation of damage with time and course of operation are key to developing an appropriate maintenance strategy. Specific mathematical tools (Kruk, 2021; Wawrzyński, 2018) or descriptive elements resulting from operational experiences (Goliasz & Pszczółkowski, 2019; Kupiec et al., 2018) are also used for this.

Two different approaches are possible in the reliability analysis of machines and means of transport: symptomatic and resourcing. In the resourcing approach, it is assumed that certain machine elements are systematically worn out and should be replaced after some time, or after a certain mileage in the case of means of transport, regardless of their technical condition (Jaźwiński & Borgoń, 1989). In the symptomatic approach we react to the symptoms of loss of the element's ability to continue to perform its function in the vehicle and replace the element out of necessity. Such symptoms may include excessive noise in the bearing units, knocks in the gearbox, tread wear in the tires, noticeable steering slack, excessive heating of the kinematic units, etc.

The choice of the appropriate approach in the maintenance strategy depends on the type of machine or means of transport (e.g. in aviation the elements determining flight safety are exchanged on the basis of resourcing strategy), the range of logistics services (international, national or local transport), the type of goods transported and other factors specific to each company.

In the symptomatic approach, it is very important to know the technical characteristics of failure of individual systems. Such knowledge allows for effective forecasting of spare parts stocks (for companies operating their own service) or planned shutdowns for periodic maintenance, targeted at specific components.

In some cases, companies, based on their own experience, decide to differentiate their maintenance strategies according to the "degree of machine use", which is indirectly related to the operating time.

In this context, the following periods can be distinguished during the life of the machine (Goliasz & Pszczółkowski, 2019; Niewczas et al., 2019):

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- period of reactive maintenance, the repair is carried out after the damage has occurred, so this is a symptomatic approach,
- period of preventive maintenance – in this strategy, repairs are planned and preventive in nature, so it is a kind of hybrid approach, also considering the resourcing for particularly important elements of the machine,
- period of predictive (proactive) maintenance – for such an approach system supporting the process of technical condition monitoring are used, e.g. planned inspections, 5S, active involvement of operators in the monitoring process.

In this context, the question arises as to whether the characteristics based on the life of a machine or vehicle or other measures characterizing the intensity of operation, e.g. the mileage of the vehicle or the actual life of the machine, are more useful in the maintenance strategy than its "record age". Users, including repair specialists, have different opinions on this matter, dictated by their own experiences and observations. Scientists try to look at this problem objectively and capture the problems of reliability in the form of appropriate characteristics and parameters that allow to compare the reliability of various types of machines or car brands, the reliability of components important from the point of view of operation in different periods of their work and (Krivtsov & Frankstein, 2004; Lawless et al., 1995; Szkoda, 2012; Wituszyński & Jakubowski, 2009).

Functional and parametric characteristics of the reliability of motor vehicles

Commonly known functional and parametric characteristics are characteristics such as the reliability function $R(t)$, failure function $F(t)$, density function $f(t)$, damage intensity function $\lambda(t)$, average time of reliable operation $E(T)$, or standard deviation $\sigma(T)$ of this time, defined in (1)–(6), where T is the time of reliable operation of the device, technical object (Barlow & Proschan, 1975; Gniedenko et al., 1968).

$$R(t) = P[T \geq t], \tag{1}$$

$$F(t) = P[T < t], \tag{2}$$

$$f(t) = \frac{\mathrm{d}}{\mathrm{d}t} F(t), \tag{3}$$

$$\lambda(t) = -\frac{\mathrm{d}}{\mathrm{d}t}(\ln R(t)) = \frac{f(t)}{R(t)}, \tag{4}$$

$$E(T) = \int_0^\infty t \cdot f(t)\,\mathrm{d}t = \int_0^\infty R(t)\,\mathrm{d}t, \tag{5}$$

$$\sigma(T) = \sqrt{E(T - E(T))^2}\,. \tag{6}$$

The above-mentioned characteristics are closely related to the time of use of the object, so they mainly concern non-renewable objects, i.e. those that are not repaired after a failure, but replaced with new ones. For example, in the car reliability tests, if we want to use these characteristics, we treat the car as a non-renewable object, but only in the sense that after the first failure we exclude it from further observation. The results of such tests can be useful only if we are interested in the moment of the first failure since the beginning of the test, they do not give a full picture of the reliability of such a technical object as a renewable one. Renewable object after failures is repaired and still in use, therefore other mathematical tools are used to describe its reliability. These include readiness, the renewal function, average time to first repair, average time between failures, time consuming repairs, etc. (Downarowicz, 2007; Figlus, et al., 2014).

Transactions on the secondary market are determined primarily by the age of the machine, especially for cars (year of production). In the case of cars, mileage is also an important parameter, but in other machines real time counters are very rarely taken into account. In this context, considering the problem more universally and systemically, it seems that it is advisable to express reliability not only as a function of the machine's service life, or more precisely its "age", but also as a function of other measures of its degree of exploitation, and in case of a car its mileage. Such approach to the issue of reliability, seems to be less popular in the literature than the classical one, in terms of time, but is noticeable, for example, in the paper (Krivtsov & Frankstein, 2006) the authors consider this problem, already posing in the title of the paper the question of how to measure the reliability of automotive components, whether to "do" it with time or mileage.

For example, for a renewable object such as a car at the work (Simiński et al., 2018) the authors presented a way to express the reliability of vehicles as a function of mileage by building the model (7), where n is the number of vehicles participating in the test and $m(s)$ is the number of vehicles that failed before reaching the mileage s.

$$R^*(s) = \frac{n - m(s)}{n}\,. \tag{7}$$

However, this model is only appropriate if we are interested in the moment of first vehicle failure. On its basis we cannot compare, for example, the failures of different vehicle systems in the same mileage range during one test, when the vehicles after the failures are repaired and continue to participate in the test.

Suggested model

The aim of this work is to present new reliability characteristics expressed as functions, of some variable expressing the measure of effective operation of a machine or device. These characteristics can be used for both renewable and non-renewable objects. Their mathematical idea reflects the essence of already known characteristics, i.e. it expresses the probability of failure but expressed as a function of a variable, not necessarily identified with time. For this purpose, we assume the following model assumptions:

- we assume that we consider objects for which we can assume that a properly defined variable s expresses the measure of work done,
- after a failure, each object/device is repaired and put into operation as fully functional with the variable s as before the failure,
- subsequent failures occur independently of the previous ones,
- we start observations when $s = s_0$,
- we assume that the object/device is used until the variable s reaches the value $s_k > 0$, after this period, we assume that the failure probability is equal to zero,
- random variable M $(M > s_0)$ expresses the value of s in the moment the failure occurred.

With such assumptions, not the objects/devices or machines are the subject of the study, but all failures of objects/devices occurring in the range $(s_0,\, s_k)$ of variable s expressing an appropriately defined measure of the work performed. We also assume that each user of the object/device assumes a hypothetical maximum value of the variable s equal s_k, after exceeding which he/she ceases to use it (scraps or sells).

In this model, the equivalent to the reliability function $R(t)$ expressing the probability of failure occurrence after time t has passed, is a function of the service life potential $R_m(s)$ defined in (8) and expressing the potential of failures acceptable to the user, measured with the probability of failure on the section from the value of s to the end of the use.

$$R_m(s) = P[M \geq s]. \tag{8}$$

This function is a decreasing function from 1 for $s = s_0$ (at the start of observation) to value 0, it expresses the potential for service life for s, it is a measure of failure risk on the range $[s,\, \infty)$.

The equivalent of the failure function $F(t)$ expressing the probability of failure before the lapse of t is the function $F_m(s)$ defined in (9) and expressing the probability of failure in the section from s_0 to s.

$$F_m(s) = P[M < s]. \tag{9}$$

If the functions $R_m(s)$ and $F_m(s)$ are absolutely continuous, there is a density function $f_m(s)$ satisfying (10) and (11).

$$R_m(s) = \int_s^{\infty} f_m(s)\,\mathrm{d}s, \tag{10}$$

$$F_m(s) = \int_0^{s} f_m(s)\,\mathrm{d}s. \tag{11}$$

Hence the density function is expressed as in (12).

$$f_m(s) = \frac{\mathrm{d}}{\mathrm{d}s}F_m(s) = -\frac{\mathrm{d}}{\mathrm{d}s}R_m(s). \tag{12}$$

Therefore, we have the estimation (13), which expresses the drop-in reliability per unit of measure of a variable s.

$$f_m(s) \approx \frac{R_m(s) - R_m(s+\Delta s)}{\Delta s}. \tag{13}$$

Another important characteristic is the damage intensity function $\lambda(t)$. Its equivalent defined for the argument s has the form given by the formula (14).

$$\lambda_m(s) = \frac{f_m(s)}{R_m(s)} = -\frac{\mathrm{d}}{\mathrm{d}s}[\ln R_m(s)] = -\frac{R'_m(s)}{R_m(s)}. \tag{14}$$

Therefore, we have the estimations (15) and (16)

$$\begin{aligned} R_m(s) - R_m(s+\Delta s) &\approx R'_m(s)\cdot\Delta s \\ &= -\lambda_m(s)R_m(s)\cdot\Delta s, \end{aligned} \tag{15}$$

$$\lambda_m(s) \approx \frac{R_m(s) - R_m(s+\Delta s)}{R_m(s)\cdot\Delta s}. \tag{16}$$

The formula (16) can be interpreted as a relative decrease in reliability/service life potential per notional unit of measure of the variable s.

An additional measure of failure may be the failure rate defined in (17), where $n(s)$ is the total number of failures in the section $(s_0,\, s]$.

$$v_m(s) = \frac{n(s+\Delta s) - n(s)}{\Delta s}. \tag{17}$$

The above formulas allow us to define empirical reliability characteristics for the argument s. We build the following mathematical model. We analyse the number of failures in the section from s_0 to s_k. We divide the range $[s_0,\ s_k]$:

$$s_0 < s_1 < \cdots < s_k$$

and introduce the following designations:

- $n(s)$ – total number of damages in the range $(s_0,\ s]$,
- s_i^* – centre of range $(s_{i-1},\ s_i]$.

Then we obtain the formulas (18)–(22) for empirical functional reliability characteristics as functions of s.

– empirical density function:

$$\bar{f}_m(s_i^*) = \frac{n(s_i) - n(s_{i-1})}{n(s)(s_i - s_{i-1})}\,, \tag{18}$$

– empirical damage intensity function:

$$\bar{\lambda}_m(s_i^*) = \frac{n(s_i){-}n(s_{i-1})}{\left(n(s_k){-}\dfrac{n(s_{i-1}){+}n(s_i)}{2}\right)(s_i{-}s_{i-1})}\,, \tag{19}$$

– empirical failure rate:

$$\bar{v}_m(s_i^*) = \frac{n(s_i) - n(s_{i-1})}{s_i - s_{i-1}}\,, \tag{20}$$

– empirical failure function:

$$\bar{F}_m(s) = P[M < s] = \frac{n(s)}{n(s_k)}\,, \tag{21}$$

– empirical reliability function/empirical service life potential function:

$$\bar{R}_m(s) = P[M \geq s] = 1 - \frac{n(s)}{n(s_k)}\,. \tag{22}$$

The above characteristics will be presented for renewable objects such as trucks based on actual data collected in one of the car service stations.

Case study

In order to present an exemplary course of the proposed characteristics, we will use data collected in the diagnostic and repair station over a period of 5 years. The study involved 10 trucks (IVECO–2, MAN–2, MERCEDES–2, RENAULT–2, VOLVO–2) used to transport construction materials. All the vehicles were loaded with similar loads and were driven under similar road conditions. Failures of these vehicles were observed in the range from 200 000 km to 700 000 km. There were 158 failures in that time, which means on average 3 failures per one car per 100 000 km. All failures were classified into 6 groups: failure of the electrical system, failure of the cooling system, failure of the brake system, failure of the steering system, failure of the drive system and failure of the suspension system. The observed mileage range was divided into 10 sub-ranges with a length of 50 000 km each. In order to simplify the accounts a unit of 10 thousand km was adopted. Each observed failure was assigned to one of the sub-ranges. In this way, a register of failures in particular ranges was obtained, broken down into groups of systems they concerned. For the collected data set, the values of individual characteristics were calculated for the total number of failures (Table 1).

Table 1
Values of the analysed characteristics for the total number of failures

Service life potential function estimator	Failure function estimator	Denisity function estimator
$\bar{R}_m(25) = 0.927$	$\bar{F}_m(25) = 0.927$	$\bar{f}_m(22,5) = 0.015$
$\bar{R}_m(30) = 0.848$	$\bar{F}_m(30) = 0.152$	$\bar{f}_m(27,5) = 0.016$
$\bar{R}_m(35) = 0.739$	$\bar{F}_m(35) = 0.261$	$\bar{f}_m(32,5) = 0.022$
$\bar{R}_m(40) = 0.619$	$\bar{F}_m(40) = 0.381$	$\bar{f}_m(37,5) = 0.024$
$\bar{R}_m(45) = 0.482$	$\bar{F}_m(45) = 0.518$	$\bar{f}_m(42,5) = 0.028$
$\bar{R}_m(50) = 0.342$	$\bar{F}_m(50) = 0.658$	$\bar{f}_m(47,5) = 0.028$
$\bar{R}_m(55) = 0.245$	$\bar{F}_m(55) = 0.756$	$\bar{f}_m(52,5) = 0.020$
$\bar{R}_m(60) = 0.148$	$\bar{F}_m(60) = 0.852$	$\bar{f}_m(57,5) = 0.019$
$\bar{R}_m(65) = 0.072$	$\bar{F}_m(65) = 0.928$	$\bar{f}_m(62,5) = 0.015$
$\bar{R}_m(70) = 0$	$\bar{F}_m(70) = 1$	$\bar{f}_m(67,5) = 0.014$
Damage intensity function estimator	**Cumulative damage intensity function estimator**	**Failure rate estimator**
$\bar{\lambda}_m(22,5) = 0.015$	$\bar{\Lambda}_m(22,5) = 0.015$	$\bar{v}_m(22,5) = 9.4$
$\bar{\lambda}_m(27,5) = 0.018$	$\bar{\Lambda}_m(27,5) = 0.033$	$\bar{v}_m(27,5) = 10$
$\bar{\lambda}_m(32,5) = 0.106$	$\bar{\Lambda}_m(32,5) = 0.060$	$\bar{v}_m(32,5) = 14$
$\bar{\lambda}_m(37,5) = 0.028$	$\bar{\Lambda}_m(37,5) = 0.096$	$\bar{v}_m(37,5) = 15.4$
$\bar{\lambda}_m(42,5) = 0.035$	$\bar{\Lambda}_m(42,5) = 0.146$	$\bar{v}_m(42,5) = 17.6$
$\bar{\lambda}_m(47,5) = 0.05$	$\bar{\Lambda}_m(47,5) = 0.213$	$\bar{v}_m(47,5) = 17.8$
$\bar{\lambda}_m(52,5) = 0.068$	$\bar{\Lambda}_m(52,5) = 0.281$	$\bar{v}_m(52,5) = 12.6$
$\bar{\lambda}_m(57,5) = 0.097$	$\bar{\Lambda}_m(57,5) = 0.378$	$\bar{v}_m(57,5) = 12.2$
$\bar{\lambda}_m(62,5) = 0.139$	$\bar{\Lambda}_m(62,5) = 0.517$	$\bar{v}_m(62,5) = 9.8$
$\bar{\lambda}_m(67,5) = 0.4$	$\bar{\Lambda}_m(67,5) = 0.917$	$\bar{v}_m(67,5) = 9.2$

Similar analyses were also carried out for the individual systems under analysis.

Graphic interpretation of the obtained results is presented in Figures 1–13. The obtained characteristics were compared using the following scheme:

- the characteristics for individual systems were compared with the characteristics determined for the total number of failures;
- the characteristics most deviating from the characteristics for the total number of failures were compared.

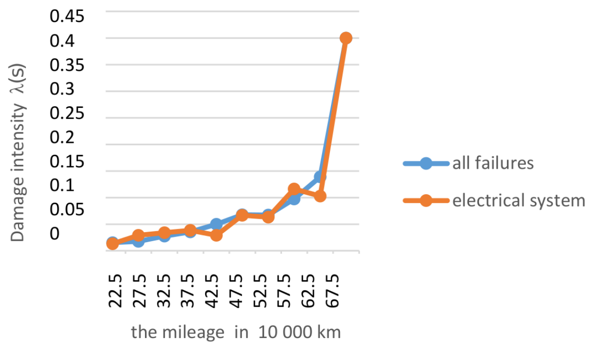

Fig. 1. Damage intensity for all failures and electrical system components as a function of the mileage

Damage characteristics of electrical system elements do not differ significantly from elements of other systems, there are periodic deviations from the general characteristics, this is typical for elements of this system where accidental events play an important role (fuse damage, "burning" of the bulb, mechanical damage to the cable, etc.).

Similar characteristics of damage are shown by the elements of the drive system, presented in Fig. 2.

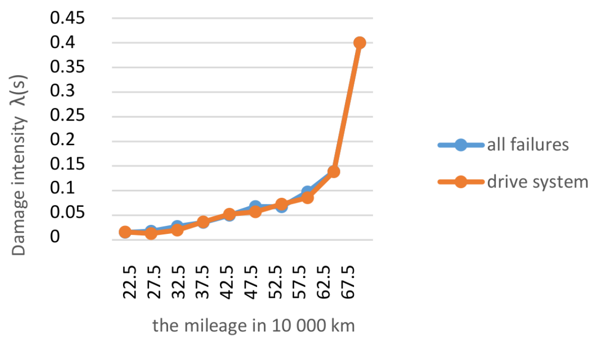

Fig. 2. Damage intensity for all failures and drive system components as a function of the mileage

In Fig. 3, we observe an increase in the failure rate of cooling system for the mileage from 400 000 km to 500 000 km, and then, probably as a result of renewal, the system shows no failure.

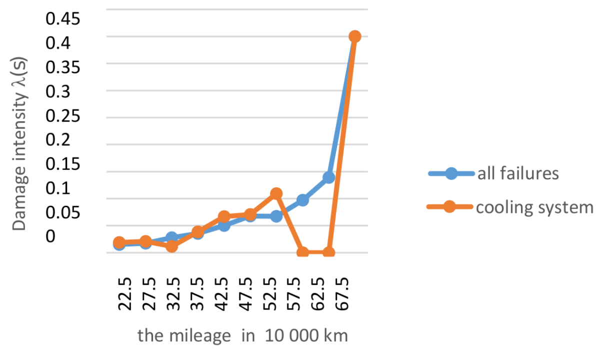

Fig. 3. Damage intensity for all failures and cooling system components as a function of mileage

In the case of the braking system, above 550 000 km, we observe in Fig. 4 clearly higher values of the damage intensity function than the comparative values for all failures, which on the graph of the service life potential function in Fig. 6 reflects a faster rate of decrease of this function for the mileage above 500 000 km compared to the service life potential function for all failures, and on the graph of the cumulative damage intensity gives significantly greater values (Fig. 5).

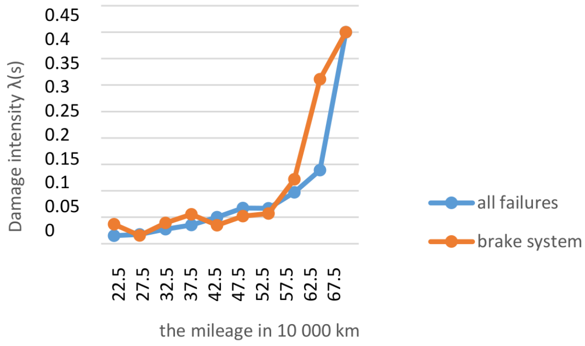

Fig. 4. Damage intensity for all failures and brake system components as a function of mileage

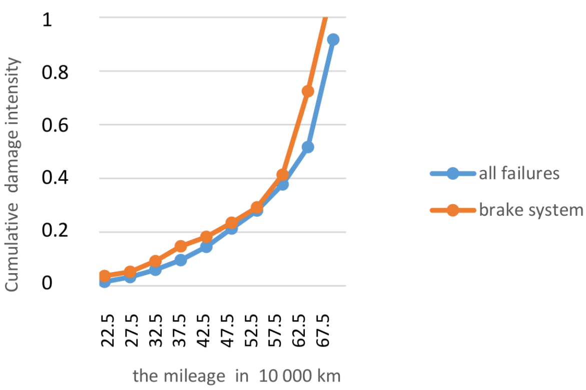

Fig. 5. Cumulative damage intensity for all failures and brake system components as a function of mileage

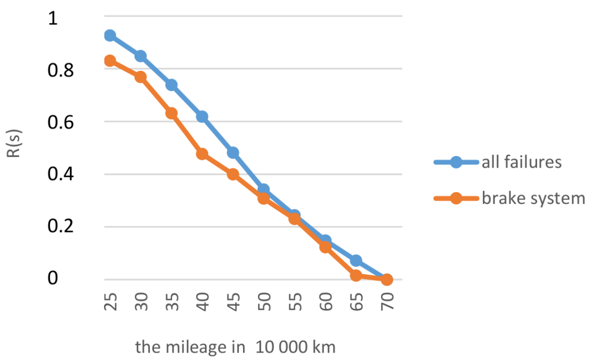

Fig. 6. Function of the service life potential for all failures and brake system components as a function of mileage

In the case of steering system, in the range from 350 000 km to 500 000 km, the values of the damage intensity function are higher than the comparative values (Fig.7), and then they clearly decrease, which may suggest the renewal of important parts of this system. On the graph of the cumulative damage intensity function, we observe the higher rate of growth in the range from 350 000km to 500 000 km in relation to the cumulative damage intensity function for all failures in this interval (Fig.8), and stabilization

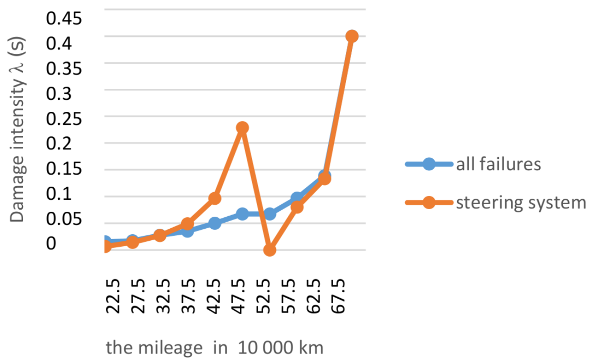

Fig. 7. Damage intensity for all failures and steering components as a function of mileage

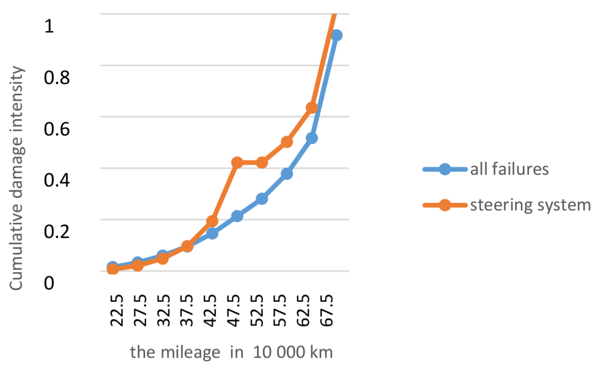

Fig. 8. Cumulative damage intensity for all failures and steering components as a function of mileage

for the values above 500 000 km of the mileage. On the graph of the service life potential function, this results in a higher decrease rate for values between 400 000 km and 500 000 km and stabilization for the further mileage (Fig. 9).

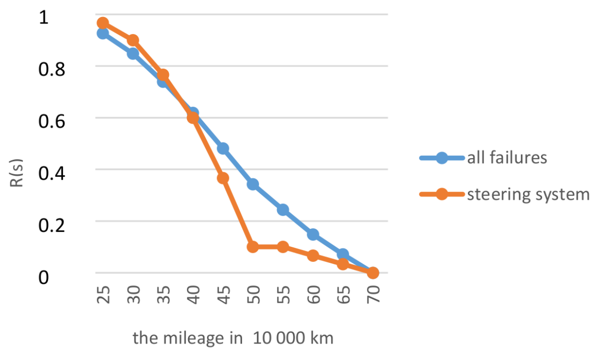

Fig. 9. Function of the service life potential for all failures and steering components as a function of mileage

In the case of suspension system, we observe a similar behavior of the analyzed functions, with the difference that the maximum value of the failure intensity function is reached for the mileage about 100 000 km greater than in the case of steering system (Fig. 10, Fig. 11 and Fig. 12).

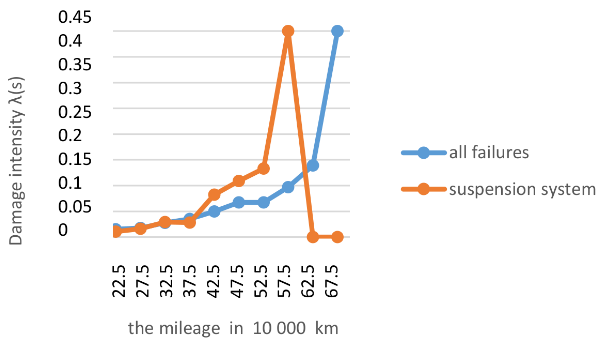

Fig. 10. Damage intensity for all failures and suspension components as a function of mileage

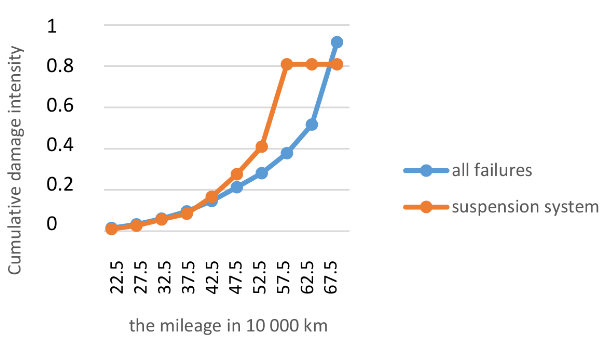

Fig. 11. Cumulative damage intensity for all failures and suspension system components as a function of mileage

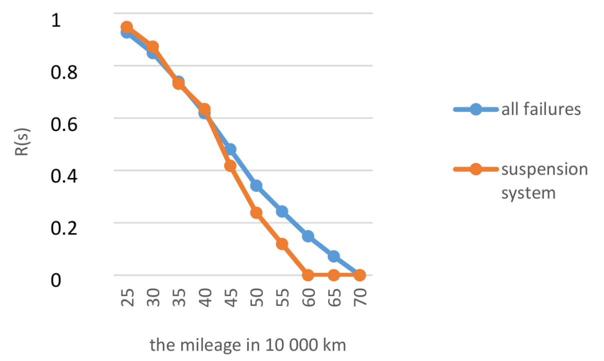

Fig. 12. Function of the service life potential for all failures and suspension components as a function of mileage

On the collective graph of the damage intensity function, we observe that the earliest (at the lowest mileage) a significant increase of the value of the this function occurs for steering system, then there is an increase in the failure rate for the cooling system, and with a further increase of mileage the number of failures increases successively for the suspension system and the brake system.

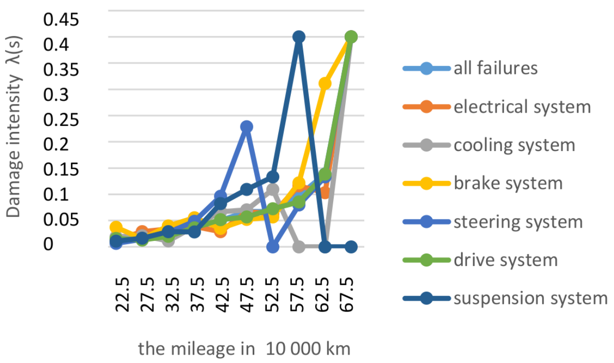

Fig. 13. Damage intensity for all systems as a function of mileage

Discussion and conclusions

The test was carried out for mileages in the range from 200 000 km to 700 000 km, i.e. in the range for which the damage intensity should be stable, which translates into a steady decrease in the service life potential. This is confirmed by the graphs of both functions, which are very similar for all systems. Some differences, in the form of increased damage intensity function values for suspension and steering systems, may result from the fact that the test applies to trucks transporting construction materials, i.e. driving with high load on largely unpaved roads.

The test covered the range of mileage from 200 000 km to 700 000 km, i.e. the mileage in which the failure rate of vehicles should obviously be stabilized and this is confirmed by the analyzed characteristics, damage intensity function $\lambda_m(s)$ is fairly flat, and the function of the service life potential $R_m(s)$ keeps a steady rate of decrease. The extension of the observation interval for mileages over 700 000 km should result in a noticeable increase in the number of failures occurring in subsequent intervals and thus the damage intensity function should increase, and the service life potential function should increase the rate of decrease. Determining the mileage value s_x, after which further operation of the vehicle is associated with the risk of higher failure rate would be tantamount to determining this mileage value, after which the vehicle operation costs increase. Such information can be useful when deciding on the company's strategy for fleet maintenance, replacement or change of use.

Comparing the received function values of $\lambda_m(s)$, $R_m(s)$ and $\Lambda_m(s)$ with failure rate values of $v_m(s)$ for all failures and for individual systems, we find confirmation of the observed trends, the highest values of this rate appear for mileages above 400 000 km.

Analyzing the results obtained, the following general conclusions can be drawn.

1. The proposed reliability characteristics based on car mileage values such as damage intensity function, cumulative damage intensity function, service life potential function, or failure rate can be useful for planning a fleet maintenance strategy for a transportation company.
2. Some characteristics, e.g. decrease in service life potential, can be used as a basis for decisions to withdraw a vehicle, e.g. from long international routes, to shorter national routes or to change the range of transported goods (except for specialized vehicles).
3. It seems that the prediction of failure of individual vehicle components is better correlated with mileage than with operating time.
4. The application of the proposed vehicle characteristics as a renewable object is closer to reality.
5. Determining the damage intensity function for different mileage ranges is very useful and makes it easier to predict the technical readiness of vehicles.

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